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A Method to Quantify the Detailed Risk of Serious Injury in Agricultural Production

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Abstract: Agricultural injuries are a valuable social sustainability indicator. However, current methods use sector-scale production data, so are unable to assess the impact of changes in individual farming practices. Here, we developed a method that adopts a life cycle approach to quantify the number of serious injuries during agricultural production processes and assess the potential impact of changes in agricultural practices. The method disaggregates agricultural production into operations and estimates the contribution each operation makes to the frequency of different types of injuries. The method was tested using data collected by survey during an expert workshop in which sixteen participants were asked to estimate the parameters related to typical dairy cattle and pig farms. Parameter estimates for specific operations varied considerably between participants, so normalized values were used to disaggregate sector-scale statistics to production operations. The results were in general agreement with the results from other studies. Participants found it challenging to quantify the potential effect of new technologies. Provided suitable empirical statistical data are available, the method can be used to quantify the risk of injury associated with individual products and provide an ex-ante assessment of future developments in farming practices.

Keywords: agriculture; safety; method development; social indicator; life cycle analysis; injuries

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1. Introduction

With the rapid global population growth, the challenge is to achieve food security while ensuring that global agriculture develops sustainably across all three sustainability pillars: environmental, social and economic [1]. To support decision-making in connection with development in agriculture, a range of indicator-based, sustainability assessment tools have been developed. These include environmental impact assessments, Sustainability Assessment of Farming and the Environment (SAFE), Sustainability Assessment of Food and Agriculture systems (SAFA) and life cycle assessments [2–4]. These combine environmental, social and economic indicators and require a wide range of multi-disciplinary themes to be assessed, weighted and aggregated [5]. Therefore, a coherent sustainability assessment remains challenging [6].

The social pillar of sustainability relates to the impact of a product, system, or process on the social wellbeing of society and stakeholders. Compared to the environmental and economic indicators, the social indicators are less well-developed [7,8]. At the international scale, there is an increasing focus on social impact as a main pillar of sustainability [9]. Life cycle assessment (LCA) is increasingly used in developing policy and prompting the development of methods appropriate to agriculture [7,9,10]. Social life cycle assessment

(SLCA) aims to assess the social impact of the lifecycle of a product or a production system [11]. SLCA is considered to be in a developmental phase, compared to the well-established environmental LCA, due to the lack of standardized indicators and a consensus on an appropriate framework [12–14]. The development of standardized methods to assess social sustainability is hindered by the subjective nature of many social factors and the lack of availability of extensive data [15,16]. Given the demand for the greater inclusion of the social dimension in sustainability assessments, there is a pressing need to improve the methods for calculating indicators concerning the social impact of agriculture.

It is often difficult to link social indicators to the production of a particular product, and even where this is possible, it requires high temporal and spatial resolution data [17]. The risk of serious injury is a strong contender as a social indicator for agricultural production for a number of reasons. A serious injury has a significant social impact and the risk of injury in agriculture is high, relative to other sectors of the economy. In developed countries, the agriculture sector is ranked among the most dangerous working environments [18–20]. For example, only 1.3% of the workforce is employed in agriculture in the United States and yet the sector is ranked third in the number of fatalities, after the construction and transport sectors [21]. Within the European Union (EU), the agriculture, forestry and fishing sector employ about 5% of the workforce but account for about 13% of fatal workplace accidents [22]. These sectors rank lower regarding non-fatal accidents but several studies suggest that there is considerable under-reporting [23–25]. Using serious non-fatal injuries rather than fatal injuries as an indicator has several advantages. They are more numerous and therefore the statistical coverage is likely to be more even with time and across the production sectors in agriculture. The greater frequency also means the statistics can be disaggregated to the different sectors of agricultural production to a greater extent without endangering confidentiality. At the same time, under-reporting is likely to be lower than for minor injuries, as they are more likely to result in a documented interaction with a regulatory authority, health service or insurance company.

The United Nations (UN) Sustainable Development Goals have become a central element of policymaking, since their UN Conference on Sustainable Development in Rio de Janeiro in 2012 [1]. Within the EU, there has been an increasing focus on using LCA to support policymaking and the development of resources to support this move [26]. The safety of the working environment has been integrated into SLCA to enable the assessment of the impacts the production and use of products has on human health and safety [27,28]. The risk of injury associated with particular agricultural sectors or general production processes can often be obtained from surveillance programs operated by government, records of insurance claims or health service records [29,30] or bespoke surveys [31]. However, as noted by [27], top-down methods of calculating indicators use national sectoral statistics that are readily-available but have high uncertainty for individual products while bottom-up methods rely on hard-to-access data concerning the details of the production processes. A pragmatic approach is to score production in relation to compliance with national or international legislation [32]. However, top-down methods only provide a general indication concerning where policymakers might make interventions or the possible impact of those interventions. The bottom-up approach is therefore to be preferred, if it is feasible. The objectives of the work reported here were to develop a bottom-up method to quantify the risk of serious injury during agricultural production and assess the likely effect of changes in production operations on this risk.

2. Methods

2.1. Background Theory

The method developed here adopts the approach used in LCA, i.e., identifying the activities that are required to generate a unit of product (e.g., litre of milk, kilogram of meat) and then assessing the impact of those activities on workplace injuries. The methodology we present disaggregates the production process into a number of discrete operations and uses a set of parameters to enable the estimation of the rate of injuries associated with each of them. Summing the rate of injuries for all operations yields an estimate of the rate of injuries associated with the generation of a unit of product.

In order to identify the frequency of injuries per production operation, it is necessary to carry out the following:

- Identify operations associated with the production.
- Estimate the frequency and duration with which each operation needs to be performed.
- Estimate the frequency of an incident occurring while an operation is performed.
- Estimate the likelihood of injury occurring when an incident takes place.

To provide information to guide policy and to provide the basis for any subsequent economic analysis, we recommend also including the identification of the types of injury associated with a particular operation.

We adopt the definition of hazard as the potential for an injury to occur, while risk is defined as the probability that a person will be injured once exposed to a hazard [33]. Here, we further specify the risk in terms of the probability of different types of injury. We envisage that the generation of a product by a given production system requires K operations and there are I types of injury. The general equation for calculating the frequency of an injury of type i that is associated with an operation k is;

$$F_{i,k} = N_k D_k E_k G_{i,k} \tag{1}$$

where, $F_{i,k}$ is the frequency of an injury type during operation k (injuries yr^{-1}), N_k is the number of times the kth operation is performed in a year (number yr^{-1}), D_k is the duration of the kth operation (yr), E_k is the likelihood of an incident occurring per unit time the kth operation is being performed (yr^{-1}), $G_{i,k}$ is the likelihood that this incident will result in an injury of type i (injuries incident^{-1}).

The frequency of a serious injury of any type during a particular operation during the generation of a product (F_k; injuries yr^{-1}) is given as;

$$F_k = \sum_{i=1}^{I} F_{i,\,k} \tag{2}$$

The frequency of all types of injury during all operations needed for the generation of a product (F; injuries yr^{-1}) is given as;

$$F = \sum_{k=1}^{K} F_k \tag{3}$$

Technological changes could have an impact on one or all parameters of an operation listed in Equation (1). For example, some of these technologies might remove the human and hence the hazard (E_k = 0), whereas others will reduce the duration of an operation (reduce D_k). To allow for the effect of changes in technology to be taken into account, we introduce factors into Equation (1) as follows:

$$F_{i,k} = n_k N_k d_k D_k e_k E_k g_{i,k} G_{i,k} \tag{4}$$

in which n_k, d_k, e_k, $g_{i,k}$, etc. take a value between 0 and 1 if the technology reduces a factor and >1 if it increases it.

In addition, it can be speculated that a technological advance could lead to the introduction of one or more new hazards.

There is no geographic scale implied in Equations (1)–(4); they can be applied to any production system for which data can be obtained. In practice, this means from the farm scale upwards. Note however, that the approach used here is product-based and in some circumstances, a given system (such as a farm) may produce more than one product. For example, a dairy farm will commonly sell surplus livestock for processing into meat. In principle, in such circumstances, it becomes necessary to partition the risk of injuries between the products (e.g., milk and meat). This is a common feature of many LCA studies [17].

Using F as defined in Equation (3), it is possible to generate three indicators that are used to characterize the risk of injury associated with the production of a particular product. The first is the Incidence Rate (I_r), which is expressed as the number of injuries per 100,000 workers [34]. This is calculated as follows:

$$I_r = \frac{F}{W} * 100,000 \tag{5}$$

where W is the number of workers within the production system.

Alternatively, the injuries can be reported as the Lost Time Injury Frequency Rate (Q_r; injuries (million hours worked)$^{-1}$):

$$Q_r = \frac{F}{Wh} * 1,000,000 \tag{6}$$

where h is the average number of hours worked per year per worker.

Finally, the injuries can be expressed as the frequency of injuries per unit product (F_p, as in LCA). This can be estimated as;

$$F_p\ (LCA) = \frac{F}{P} \tag{7}$$

where P is the production of the system (production units yr^{-1}).

2.2. Data Collection Method

Collecting data to calculate sustainability indicators for agricultural products is made difficult by the structure of production. Most other major industries are dominated by relatively few companies whereas agricultural production occurs on numerous, spatially dispersed units (farms). The opportunities for identifying potential participants for a workshop will vary geographically. Postal or internet surveying may be feasible, if a suitable database of contact addresses is accessible and can be utilized within the relevant data protection legislation. This option was not available for the current study. However, in Denmark, a high proportion of farmers are members of one of the 29 local farming associations. These farming associations are responsible for providing advice to farmers on a wide range of matters, including on health and safety. This means that they have a good overview of the local farming practices and issues relating to safety. We therefore had an opportunity to use the Delphi method for obtaining data [35]. However, the resources available were strictly limited and only sufficient to support a one-day workshop (including travel). Since a full implementation of the Delphi method was not possible, the data collection should be considered as a proof of concept of the application of the background theory. The sole selection criterion for the farming associations to which invitations were sent was that it should be possible to attend the meeting place (mid-Jutland) without requiring overnight accommodation. Invitations were sent to 21 of the farmers' associations. The associations were asked to send a representative who had a particular expertise in farm safety. Sixteen participants attended the workshop, representing fifteen different farmers' associations. The responsibilities of the participants within farmers' associations varied, with three heads of associations, eight representatives with special responsibility of safety and five ordinary farming members.

2.3. Organisation of the Workshop

The workshop was held at the Aarhus University's Research Center Foulum, central Jutland, on December 2, 2019. The workshop was organised in two sessions and a questionnaire was prepared to collect quantitative data in each session. In the first, the objective was to obtain parameter estimates to quantify the risk of injuries associated with a range of operations. In the second, we were seeking to assess the likely effectiveness of interventions to reduce these injuries. Although a range of educational, regulatory and technical interventions are possible, time constraints meant we were only able to consider technical interventions. Each session started with an introductory presentation. The introduction to the first session presented the aim of the method and guidance on the first questionnaire. The introduction to the second session was on technological developments on farms and guidance on the second questionnaire.

The questions were posed in terms of cases, as we felt the participants would more readily understand this approach. Two production systems were defined; dairy cattle and pig production. Livestock farms were chosen as the use of machines, handling equipment and working with animals are common causes of accidents [36–38] and because dairy and pig production are the two major production systems in Denmark. Guided by data from Statistics Denmark, both farms were assigned a field area of 175 ha. The dairy cattle farm consisted of 130 dairy cows plus breeding cattle, with a milk production of 10,000 litres cow^{-1} yr^{-1} and an annual workforce of one farmer and one worker. The pig farm had a production of 3500 finishing pigs yr^{-1}, with an annual workforce of one farmer and two workers. In both cases, all juvenile animals were reared on the farms. Prior to the second session, the participants were divided into two groups based on their area of expertise (i.e., dairy cattle and pig groups). Consequently, nine participants were asked to complete the questionnaires related to pig production and seven for dairy production.

The SurveyXact® system [39] was used to construct the questionnaires. These questionnaires were made accessible to the participants during the workshop, using their laptop, tablet or mobile phone. The data were collected individually from each participant and all questionnaire responses were anonymised. The participants consented in writing to the workshop procedures, prior to the first questionnaire. The SurveyXact® system allowed the data collected to be graphically presented to participants, immediately after collection had been completed. Both English and Danish language versions of the questionnaires were prepared but only the Danish version was made available to the participants.

After completion of the surveys, the participants were asked to discuss a number of questions that were aimed specifically at obtaining recommendations for measures to reduce the injuries occurring in Danish agriculture. This session of the workshop did not contribute to the data collection, but its inclusion was considered important to motivate the attendance of the participants. The questions asked and the results are in Supplementary Materials Section B.

2.4. Development of the Questionnaires

Discussions with safety consultants from the Danish agricultural advisors organisation identified a number of types of operation that were accident hotspots. The categories of operations were therefore chosen to allow more detail to be gathered for the riskier types of operation. The operations required for producing an agricultural product on both farm types were divided into main operations (machine repairs, building repairs, feed production, feeding, indoor movement, livestock treatment and manure management), with milking and outdoor movement of cattle as additional operations on the dairy farm. Feed production was defined as ploughing, sowing, plant protection, harvesting and feed processing, and manure management was defined as animal housing cleaning, emptying manure storage and manure spreading.

The first questionnaire aimed to estimate values for the following:

1. The frequency with which each operation is performed (days yr^{-1}).
2. The duration of each operation when it is performed (hours).
3. The likelihood of a potentially serious incident occurring (events yr^{-1}).
4. The likelihood of a potentially serious incident actually leading to a serious injury (injuries/event).
5. The likelihood that the injury would be of a given type (e.g., cutting, crushing).

For questions 1 and 2, participants were required to input numerical values. For questions 3, 4 and 5, categorical values were used. For question 3, the categorical values were low (once per 5 years), medium (once per year), high (three times per year) and irrelevant in the case that there is no likelihood that an incident would take place during the operation. For questions 4 and 5, the categorical values were very low (1 in 10,000), low (1 in 1000), medium (1 in 100) and high (1 in 10). A complete version of the first questionnaire is presented in the Supplementary Materials Section A.

In the second questionnaire, the participants were asked to quantify the reduction in injuries that might be expected when using (a) existing production and safety technologies and (b) technologies that they expect to be available in the future. The second questionnaire was structured in the same way as the first questionnaire with respect to the categorisation of operations and the order in which they were presented. The potential for technologies to reduce the risk of injuries were presented as categorical values; none (0%), low (0 to 33%), medium (34 to 67%), high (68 to 99%) and complete (100%).

The software used to present the online questionnaires to the participants allows real-time error checking. The error checking implemented in this study was as follows. For the annual frequency of operations, the input was limited to the range 0 to 365 inclusive. For the duration of each operation on the day on which it was performed, the input was limited to the range 1 to 24 inclusive. For all categorical questions, proceeding to the next set of questions was prevented, if one or more questions remained unanswered for the current set. The software allowed participants to scroll backwards and change earlier entries if they wished.

3. Results

3.1. Current Practice

During the post-processing of data, it was discovered that due to a technical problem with the survey software, the participants were not confronted with the question concerning the frequency and duration of the milking operation. As a result, it was necessary to obtain an estimate from an alternative source. In a survey of 157 Danish dairy farmers, [40] had 90 responses and found that on average they could milk 106 cows per hour i.e., the time spent by workers per cow was on average 0.566 min. From data held by the Danish dairies, they could also determine that 8% of cows were milked three times per day and 92% twice per day. For the case study dairy farm, this means that the duration of milking would be 932 h yr^{-1}.

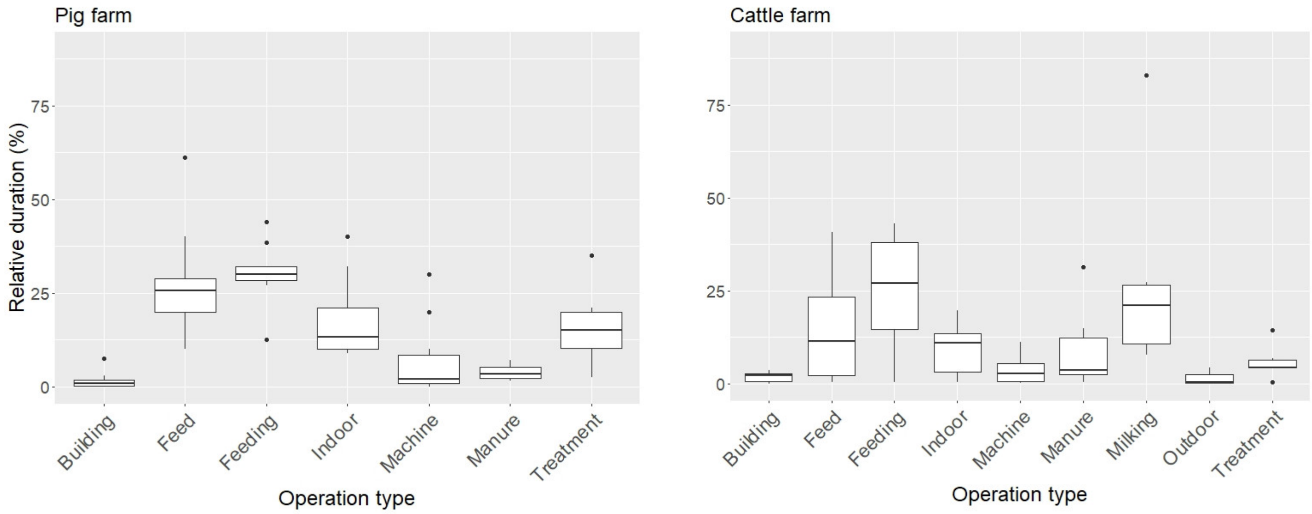
There was a high variability in participants' responses to all questions (e.g., see Supplementary Materials Section C) and it is clear that some estimates were unrealistic. For example, the average number of working hours for a worker on Danish farms is 1665 h yr^{-1} [41], yet the total time spent on production operations on the case study farms as estimated by the participants to range between 100 and 5200 h yr^{-1}. We found that the participants were consistent in their estimates, i.e., that a given expert consistently under- or overestimated their responses, compared to the average for all participants. Therefore, for many purposes here, the data were normalized for each participant as follows; for a given factor X:

$$R_x = \frac{X}{\sum_{k=1}^{K} X_k} \tag{8}$$

where R_x is the normalized value of X.

The non-parametric Friedman test was used to determine whether the differences between the medians of the frequency of injuries for the operations were statistically significant. The test uses multiple comparisons to rank the median. A Wilcoxon signed-rank test with Bonferroni [42] adjustment was used to adjust the p values.

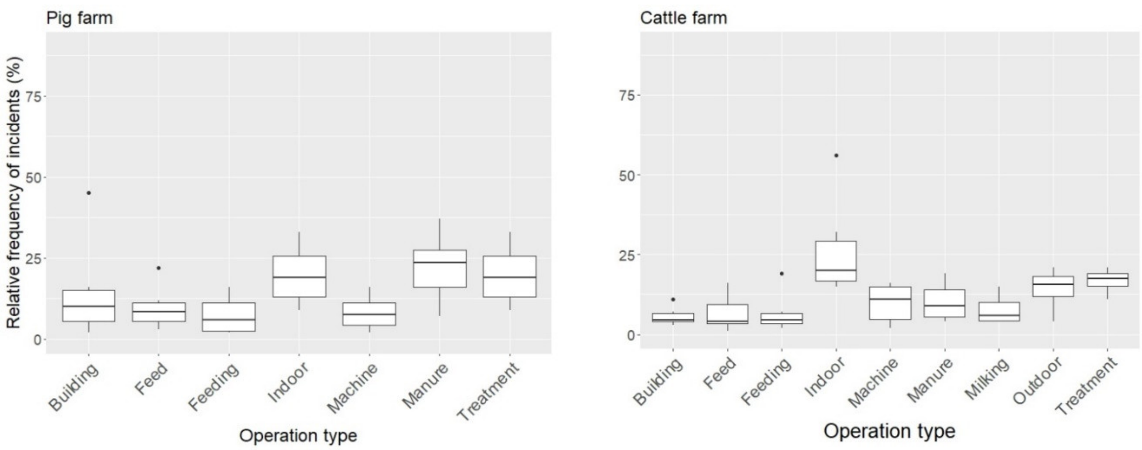
Feed production, feeding and indoor movement of animals were important operations on both farm types, with the addition of the treatment of animals on the pig farm and milking on the dairy farm (Figure 1). The adjusted p-values are 0.0001 and 0.008 for pig and cattle farms respectively, indicating that the medians of the ranked operations are significantly different.



(**a**) (**b**)

Figure 1. Relative annual duration of operations (N_kD_k in Equation (1), normalized as in Equation (8)) on: (**a**) pig farm; (**b**) cattle farm. The operations listed are building repairs (Building), feed production (Feed), feeding animals (Feeding), indoor movement of animals (Indoor), machine repairs (Machine), manure management (Manure), Milking, outdoor movement of animals (Outdoor), veterinary treatment of animals (Treatment). The box plots show the four quartiles, with extreme values shown as points.

The likelihood of potentially dangerous incidents on pig farms was particularly associated with the treatment or movement of animals and during manure management (Figure 2). The adjusted *p*-values are 0.0004 and 0.002 for pig and cattle farms respectively, indicating that the medians of the ranked operations are significantly different. For the dairy farm, a higher likelihood of potentially dangerous incidents was more associated with the indoor and outdoor movement of cattle and the treatment of animals than with other operations.



(**a**) (**b**)

Figure 2. Relative frequency of potentially dangerous incidents (E_k in Equation (1), normalized as in Equation (8)) on: (**a**) pig farm; (**b**) cattle farm.

For the pig farm, there was no clear pattern in the estimates of the percentages of potentially dangerous incidents that would result in injuries, except that the values were considered low for feed production and feeding (Figure 3). The percentages of potentially dangerous incidents on the dairy farm that would result in injuries was judged to be the greatest for the indoor and outdoor movement of animals, and the treatment of animals, although the variation in estimates was high for the indoor movement of animals (Figure 3). The adjusted p-values are 0.0043 and 0.12 for pig and cattle farms, respectively, indicating that the medians of the ranked operations for pig farm are significantly different, whereas those for cattle farm were not.

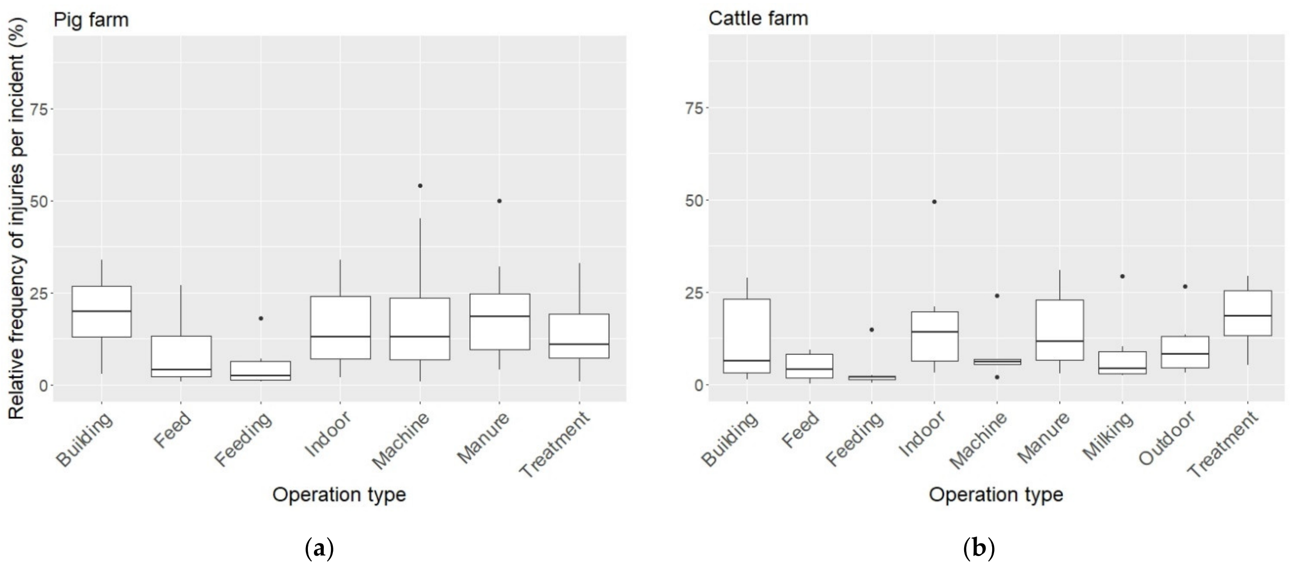


Figure 3. The percentage of potentially dangerous incidents that would result in an injury on: (**a**) pig farm; (**b**) cattle farm. This is calculated as $\sum_{i=1}^{I} G_{i,k}$ (see Equation (1)) and normalized as in Equation (8).

For both farms, a high risk was associated with operations involving the direct interaction between workers and livestock (indoor/outdoor movement of animals, treatment of animals) (Figure 4). For the pig farm, the risk was also similar for building repairs and manure management. The adjusted p-values are 0.002 and 0.02 for pig and cattle farms respectively, indicating that the medians of the ranked operations are significantly different.

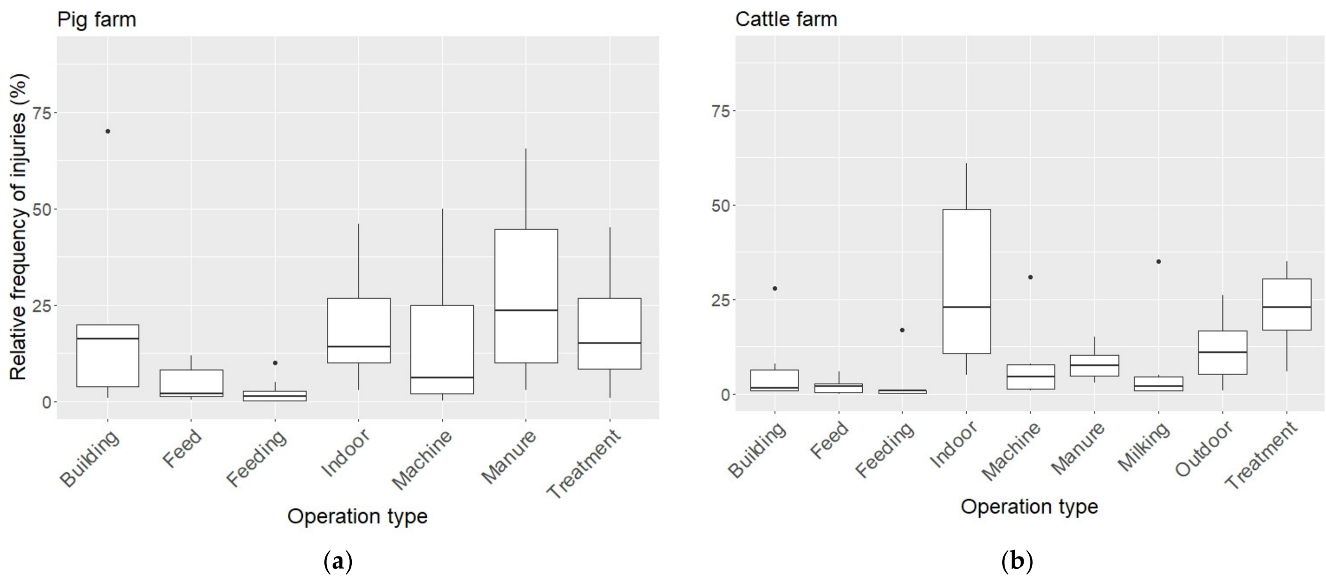


Figure 4. Relative frequency of injuries (F_k in Equation (1), normalized as in Equation (8)) for: (**a**) pig farm; (**b**) cattle farm.

Dividing the data shown in Figure 4 by the relative duration of operations (Figure 1) gives an indication of the intensity of the risk of injury for each operation. A value > 1 indicates that the operation is more than averagely risky per unit time during which it is in progress. This was the case for the outdoor movement of animals on the dairy cattle farm and for building repairs for both farms.

The type of injury expected by the participants differed considerably between operations for pig farm: poisoning for manure management, falling for feeding and repairing of building, crushing for treatment and indoor movement of animals, and crushing and cutting for feed production and repairing machines (Figure 5). The situation was similar for the dairy farm, with crushing injuries predominating for indoor movement, milking and treatment of animals, cutting predominating for feeding and repair of machinery, poisoning predominating for manure management and falling predominating for building repairs and outdoor movement of animals (Figure 5).

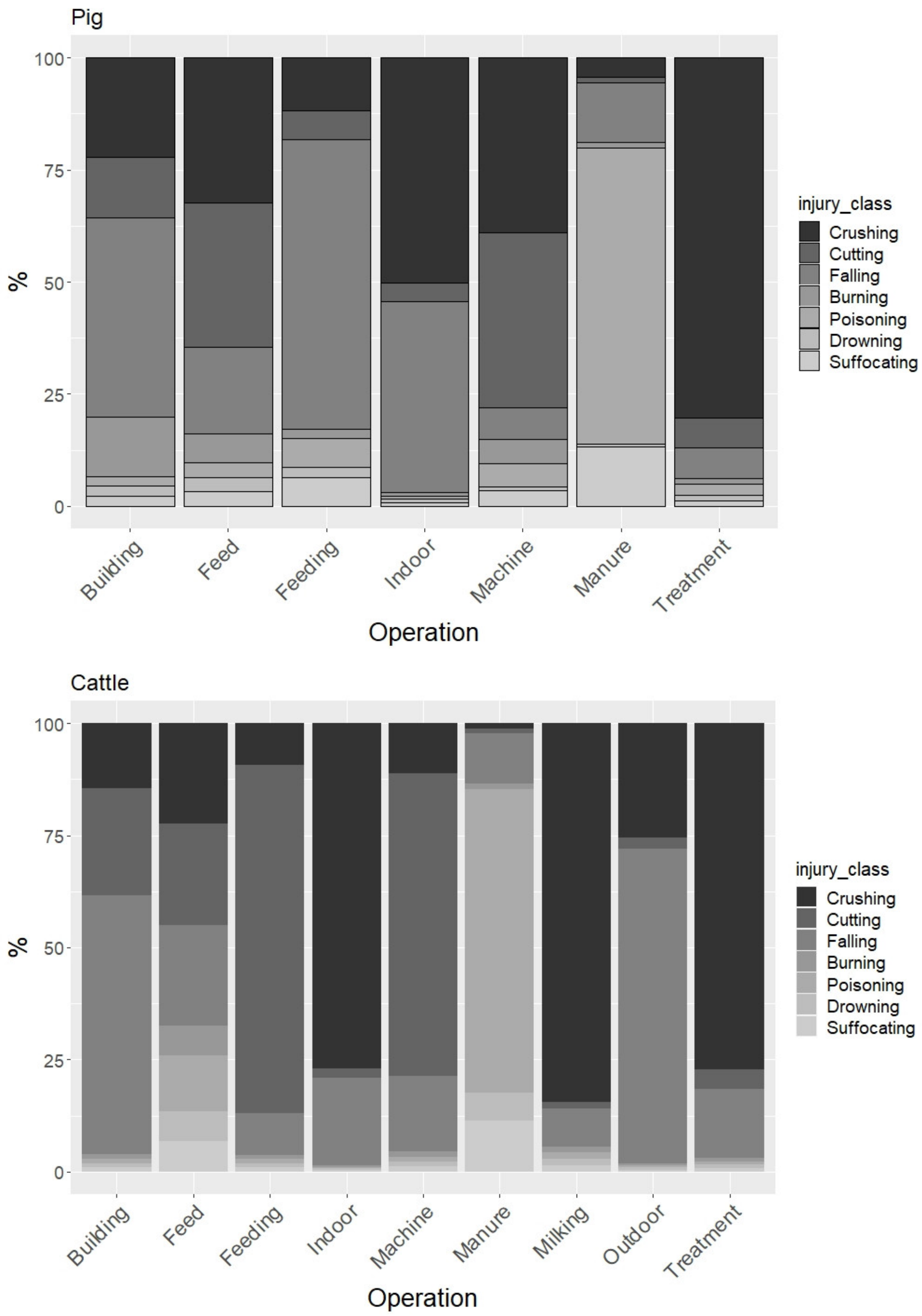


Figure 5. Distribution of types of injury for each operation for pig farm and cattle farm.

3.2. Scaling Up

Applying Equation (1) to the data yields an estimate of the number of injuries that would occur per unit time spent on production-related operations on the dairy and pig farms. To allow direct comparison between farm types, the Incidence Rates (injuries (100,000 workers)$^{-1}$ yr^{-1}) were calculated by dividing the injuries per farm for each operation by the number of workers on the farm and multiplying by 100,000 (Figure 6).

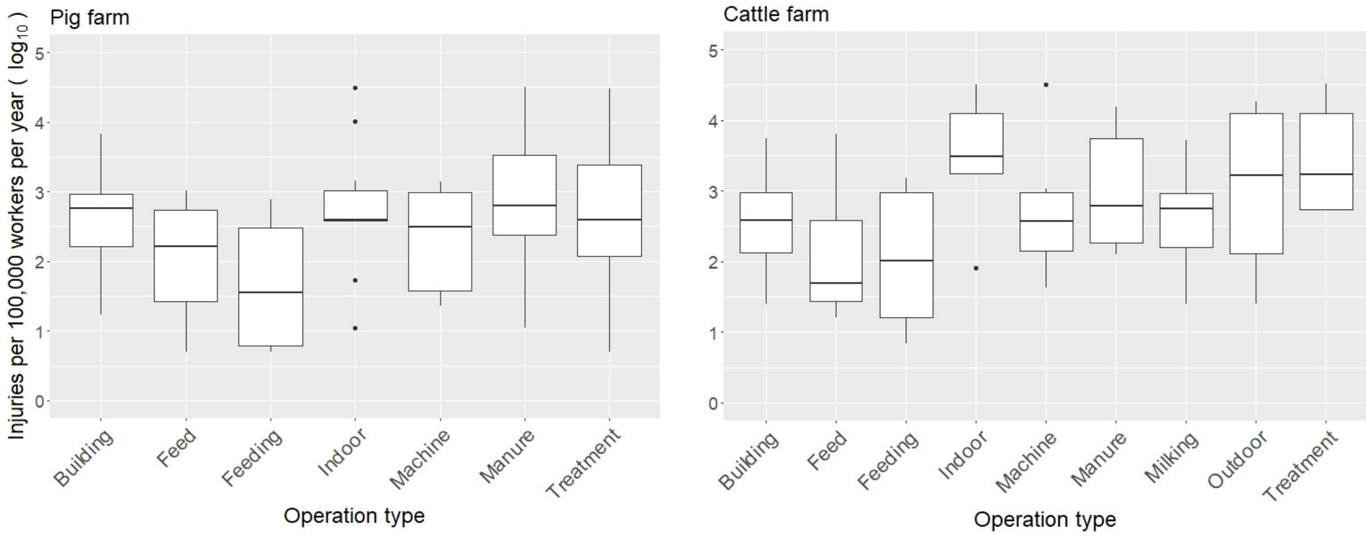


Figure 6. Incidence rate on a logarithmic scale (injuries (100,000 workers)$^{-1}$ yr^{-1}) for the operations on: (**a**) pig farm; (**b**) cattle farm.

Using the median values from our case studies, the incidence rate and the lost time injury frequency were calculated using Equations (5) and (6), respectively (Table 1). Using Equation (7), the median number of injuries per litre of milk is 2.220×10^{-7} and the median frequency of injuries per kilo of meat is 4.262×10^{-7} (assuming a weight at slaughter of 110 kg and a killing-out percentage (meat only) of 62%).

Table 1. Incidence Rate and Lost Time Injury Frequency Rate for pig and cattle farms.

Production Type	Median Incidence Rate	Median Lost Time Injury Frequency Rate
	Injuries (100,000 Workers)$^{-1}$ yr^{-1}	Injuries (1 Million Worked Hours)$^{-1}$
Pig	3556	214
Cattle	14,446	868

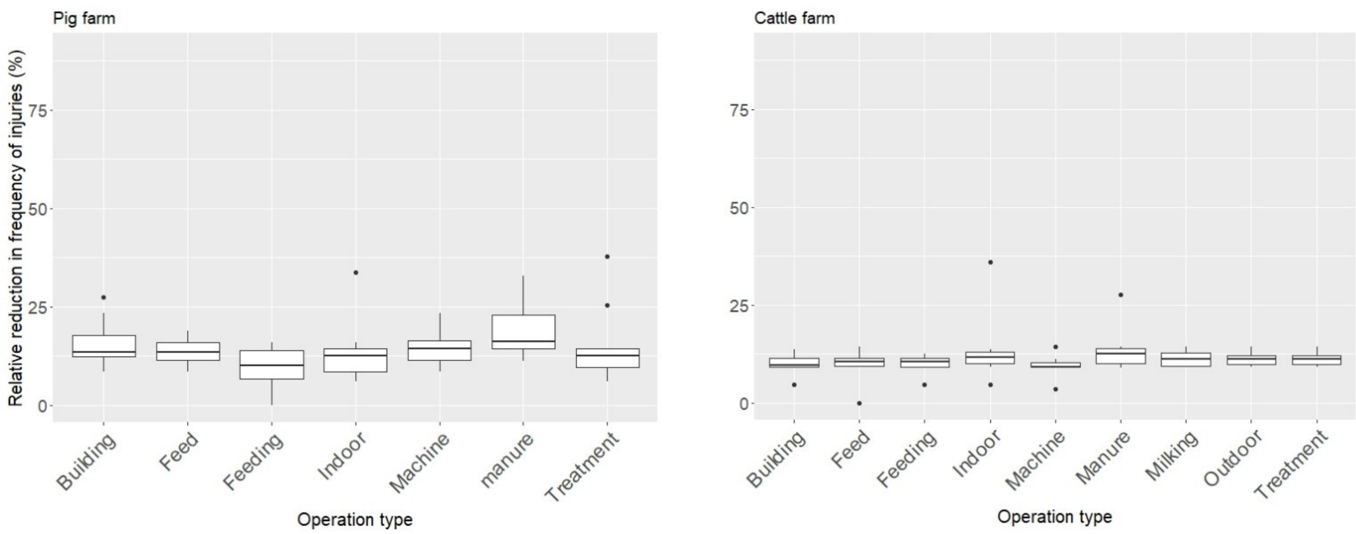
The frequency of each type of injury was summed across operation types for each participant and the median was calculated for each of the two farms. The distribution of the total median frequency of injuries across injury types was then calculated (Table 2).

Table 2. The frequencies of injury types at the farm scale for the pig and cattle farms.

Production Type	Crushing (%)	Cutting (%)	Falling (%)	Burning (%)	Poisoning (%)	Drowning (%)	Suffocating (%)
Pig	33	18	29	2	12	1	5
Cattle	48	8	39	0	4	1	1

3.3. Potential for Reduction in Injuries

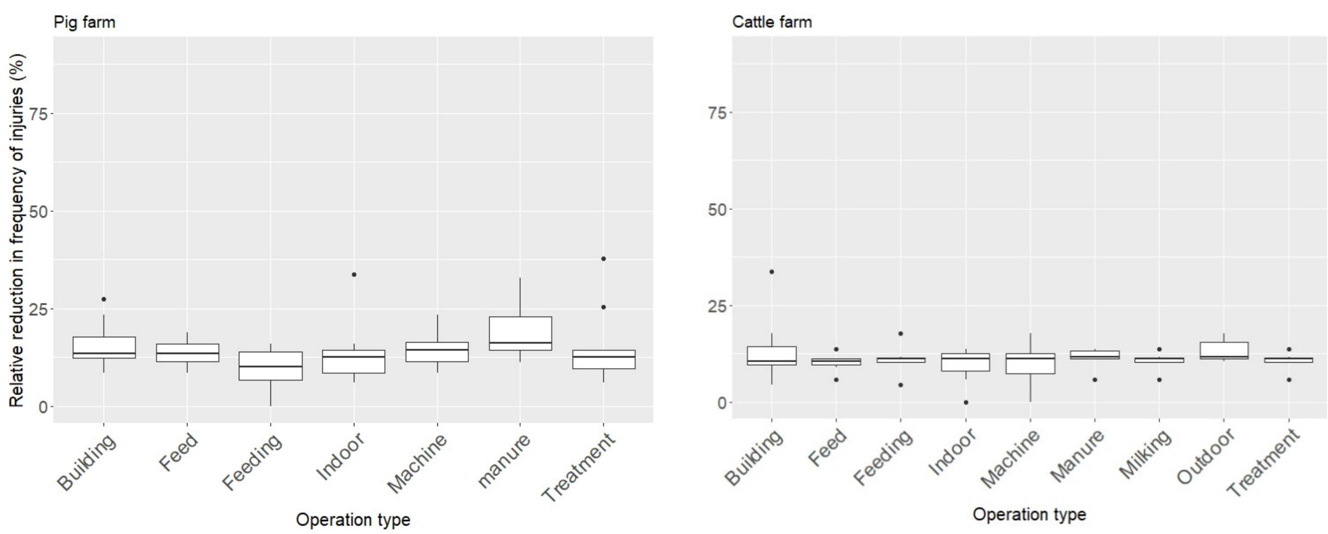
For the pig farm, the extent to which the participants considered existing safety technologies could reduce the risk of injuries was slightly higher with a greater variation between and within operations compared to the estimates for dairy cattle farm (Figure 7). The elements of Equation (4) that contributed to these results are shown in Figures 3–5 in Section D in the Supplementary Materials.



(a) (b)

Figure 7. Estimated relative reduction in injuries using existing technologies on: (**a**) pig farm; (**b**) cattle farm.

As for the existing technologies, there was a difference between the dairy and pig farms in the extent to which the participants considered that there was the potential for a reduction in the frequency of injuries through the implementation of new technologies in the future (Figure 8). The elements of Equation (4) that contributed to these results are shown in Figures 6–8 in Section D in the Supplementary Materials.



(a) (b)

Figure 8. Estimated relative reduction in injuries using new technologies on: (**a**) pig farm; (**b**) cattle farm.

4. Discussion and Perspective

4.1. Comparison with Previous Studies

The large variation in estimates between participants' responses to questions leads to a wide range in the incidence rate (Figure 6), indicating that the absolute values cannot be used directly. However, the normalized estimates of the frequency of injuries at an operation level (Figure 4) show a pattern that is recognizable from the statistics of agricultural accidents [30,31]. Activities requiring a direct interaction with animals, such as the indoor movement and treatment of animals, have a higher frequency of potentially dangerous incidents and serious injuries than other operations [24,37,43,44]. Using the absolute data values to calculate the incidence rates of serious injuries yields estimates that are higher by a factor of two (pig) and nine (dairy cattle) than the 1593 per 100,000 workers reported for Danish agricultural workers [22] (Table 1). Note that in Denmark, a serious injury is one that means the subject cannot work for a period of three or more weeks. This probably indicates an overestimation by the participants, especially for the dairy cattle, but it is important to note that the statistical record relates to all agricultural production systems, whereas our study focused on two livestock production systems that are associated with a particularly high risk of injuries. In addition, the empirical statistics may include workers engaged in administrative activities, which the survey did not include.

The incidence rates for dairy cattle and pig production found here straddled the values (per 100,000 workers) found for non-fatal injuries in the USA of 7400 for livestock production by [44] and 4800 and 7000 for all agriculture by [45] and [46], respectively. The equivalent values reported for 2013 for other European countries vary from 5 to 5331, but the foundation for these values is uncertain [47]. The values found in the current study are therefore closer to those found elsewhere than in Denmark, although caution is required when comparing the statistics for non-fatal injuries. As noted earlier, under-reporting of non-fatal accidents is an issue and the degree to which this occurs could vary between countries. The criteria for distinguishing between serious and minor injuries may also vary. Finally, the incidence of injuries might be expected to vary with such characteristics of agriculture as farm size, the employment of non-native language migrant workers, educational standards and the culture of farm safety.

The most common injury type for both farm types was crushing, and this was particularly so for the cattle farm (Table 2). Given that this injury was mainly associated with direct interactions with livestock (Figure 5), the greater prominence on the cattle farm compared to the pig farm can probably be attributed to the difference in body size between the two species. In common with other studies [30,31], falling was identified as an important injury type on both farm types. Cutting was the third most frequent injury on both farms but whereas the risk was spread across most operations on the pig farm, on the cattle farm, the risk was concentrated on feeding and repair of machinery (Figure 5). Poisoning was identified as the third most frequent injury on both farms, and in both cases, was predominantly associated with manure management. The values for suffocation can most likely be added to these values, since they too were mainly associated with manure management and there is little distinction between being poisoned by hydrogen sulphide or suffocated by carbon dioxide and methane. Drowning was not identified as a major injury associated with manure management, as has been the case elsewhere [48]. This may be because this latter study concentrated on children and younger adults, and because of differences in manure management between the USA and Denmark (e.g., accessible slurry lagoons versus less accessible slurry tanks).

The comparison of the results of this method with previous studies suggests that the absolute estimates of the parameters of Equations (1)–(7) should not be used directly but that the normalized values can be used to disaggregate more reliable, sector-scale statistical information.

4.2. Perspectives

The method developed here enabled detailed data to be collected concerning the operations involved in the production of cow milk and pork but should be applicable to other agricultural products. The disaggregation of production into separate operations allows the likely consequences of changes in agricultural production operations or the implementation of measures to increase safety on the frequency of injuries to be quantified. This allows potential developments in agriculture to be captured by the sustainability indicator.

The results found here will be mainly applicable to Denmark; therefore, for the method to be used, it will be necessary to obtain location-specific data. Even well-resourced countries are likely to experience difficulties collecting statistical data with the detail needed to parameterise Equations (1)–(7), so it would be necessary to conduct a survey in the geographic area under consideration and that the survey be structured to take into account the nature of agricultural production (e.g., farm size). A range of factors will determine whether to use the workshop approach adopted here or to survey farmers directly. Participatory expert assessments can be a reliable and time-efficient method to collect quantitative information, when the data are not available or there is a clear gap in knowledge [49,50]. Using the Delphi method provides an opportunity to refine responses and rectify misunderstandings. Resource limitations prevented a full implementation of the Delphi method in the current study, and it is likely that if this were done, the large and systematic variation between participants in the responses to the questionnaires found here would be reduced. Nevertheless, it may often be advisable to normalise the data and then combined the results with less variable empirical data, such as national injury statistics; this approach has been previously proposed [17]. The method is well-suited for use in SLCA but will not completely eliminate the need for the use of allocation methods on farms or production systems that produce more than one product, since some operations (e.g., building maintenance and repair) will be shared across products.

An advantage of the method developed here is that the increased knowledge of the details of production and the link to the risk of injury improves the basis for prioritising interventions to reduce that risk. It also provides a structure for assessing the safety side-effects of technological advances in agricultural production. In the longer term, data concerning the duration and frequency of production operations will benefit from the increased availability of data from digitally enabled smart machinery on farms [51]. However, the workshop participants reported that they found it challenging to assess the potential for current safety technology to reduce the hazards and risks associated with production operations. The variation seen in Figure 7 may reflect a lack of knowledge concerning the range of technologies currently available but may also reflect uncertainty concerning the extent to which these technologies have already been adopted by farmers. The participants reported that they found it even more challenging to assess the consequences of the introduction of new technologies (Figure 8). The assessments of the implementation of both current and future technologies in particular would benefit from a more comprehensive application of the Delphi method than was possible in the current study, since it would allow a greater opportunity to reflect on and discuss novel technologies.

The accuracy of the values obtained using the method developed here depends crucially on the availability of good quality statistical data concerning both agricultural injuries and the structure of the agricultural production system. While detailed agricultural production statistics will be available for many countries, the accuracy and availability of injury data will vary between countries and data sources [23,30,52] and the under-reporting of injuries appears to be a global problem [28,53]. The applicability of the method developed here at a given location is therefore primarily determined by the availability of good quality and detailed statistical data concerning agricultural injuries.

5. Conclusions

The method developed here enables an assessment of the injuries associated with current agricultural production and, by considering all the major processes involved, permits a quantitative assessment of the consequences of changes in farming activities and technological interventions. However, the model on which the method is based requires access to detailed data concerning the risk of injuries associated with specific production operations. Experience from a workshop suggests that expert assessments can provide these data. Although experts' estimates for the parameters required varied considerably, there was general agreement between the normalized estimates of injury statistics, and other statistical and literature sources. The results indicated that serious injuries are more likely to occur when there is direct interaction with animals. Disaggregating injuries to the scale of the production process enables such higher risk operations to be identified. However, more developmental work is still required, especially with regards to assessing the impact of new technologies. Nevertheless, we conclude that the method has the potential for general applicability in situations where good quality and detailed statistical data concerning agricultural production and injuries are available.

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